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Recommended Practice for the Use of
Electromagnetic Flowmeters in
Wastewater Treatment Plants

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RECOMMENDED PRACTICE FOR THE USE OF ELECTROMAGNETIC
FLOWMETERS IN WASTEWATER TREATMENT PLANTS

by

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FOREWORD

The U. S. Environmental Protection Agency was created because of increasing public and Government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

ABSTRACT

Electromagnetic flowmeters that conform to the guidelines described in this document can be used to measure the volumetric flowrate of all liquids and sludges normally encountered in wastewater treatment plants, provided that adequate inspection and maintenance are performed as recommended to contend with potential deposits and other effects of the harsh fluids.

Electromagnetic flowmeters should be accurate to the lesser of 1 percent of full scale or 3 percent of actual flowrate. These flowmeters are not necessarily immune to the effects of approach velocity distribution. Specific approach conditions are cited which must be observed during installation in order to minimize velocity-distribution errors.

Upon installation, electromagnetic flowmeters should be hydraulically tested, by a method equivalent to that described, to provide an acceptance test and/or initial calibration. Continuing and frequent performance monitoring subsequent to initial testing is particularly important for electromagnetic flowmeters in treatment plants. Methods for accomplishing this are suggested.

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1. SCOPE

- 1.1 This document covers the use of electromagnetic flowmeters for in-plant flowrate measurement of raw influent, treated effluent, and wastewater in intermediate stages of treatment as well as various types of liquid sludges.
- 1.2 For the purposes of this document, "use" of electromagnetic flowmeters is considered to include: requirements for the design and construction of the primary and secondary elements; requirements for installation of the equipment; recommendations for performance checks, operation and maintenance.

2. DEFINITIONS

- 2.1 Accuracy -- The sum of the systematic error (bias or difference from the "true" value) and the precision at a stated confidence level (e.g., in terms of a number of standard deviations). In the case of flowmeters, the true value is usually determined from a basic calibration method.
- 2.2 Flow converter -- The element of the secondary system that converts the output electrical signal to flowrate units on a dial, digital, chart or other readout.
- 2.3 Flow tube -- The part of the primary that forms a pipe-like conduit.
- 2.4 Precision -- The reproducibility or repeatability of a measurement.
- 2.5 Primary -- The element of a measuring system that generates a measurable change in a parameter. In this case, the primary consists of the flow tube, the coils and yoke that produce a magnetic flux, and the electrodes.
- 2.6 Quadrature noise -- Electrical noise that is 90 degrees out of phase with the desired flow signal.
- 2.7 Repeatability -- See precision.
- 2.8 Reynolds number -- A dimensionless number that expresses the ratio between inertial and viscous effects in a flow. Low Reynolds numbers (below about 2000 for pipe flow) correspond to laminar flow.
- 2.9 Secondary -- The portion of the measuring system that amplifies and/or conditions the signal from the electrodes into an output proportional to the flowrate and further usually converts it to a readout in flowrate units. Part or all of the secondary may be mounted directly on the primary.
- 2.10 Threshold conductivity -- A minimum electrical conductivity above which changes of conductivity of the flowing liquid have a negligible effect on the measurement.
- 2.11 Weight function -- A theoretical function that weights the contribution of each part of the induced voltage in the flow section to the total sensed by the electrodes.
- 2.12 Zero drift -- A change with time in the output reading for the no-flow condition.

3. BACKGROUND

3.1 Principle of Operation

3.1.1 Flow-tube meters. The operation of electromagnetic flowmeters is based on the Faraday law of electromagnetic induction. If flow of a conductive fluid in a pipe is normal to a magnetic field, an electromotive force is induced across the fluid in a direction normal to both the magnetic field and the flow. The induced voltage is measured by placing insulated electrodes across the pipe so that a line connecting them is perpendicular to the magnetic field. See figure 1.

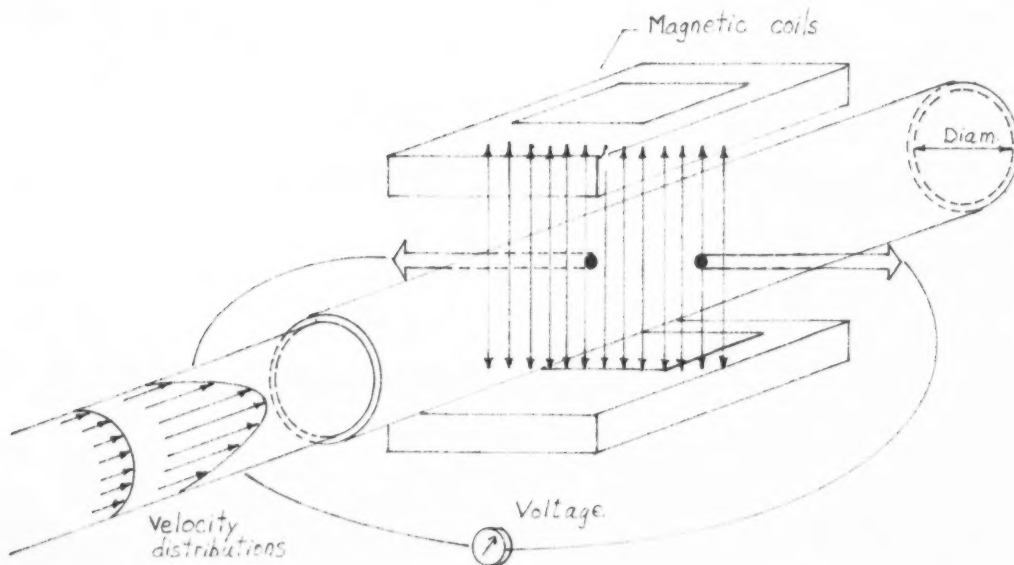


Figure 1. Flowmeter schematic.

For an axisymmetric pipe flow and a uniform magnetic field the output voltage, E , is given by

$$E = k B L V \quad [1]$$

where L is the distance between electrodes, V is the average velocity of the flow, B is the magnetic flux density and k is a coefficient that is constant for a given meter. The volumetric flowrate, Q , is then

$$Q = \pi D^2 V / 4 \quad [2]$$

where D is the diameter of the flow tube and is often, but not always, the same as L .

The fluid being measured must be conductive. The threshold conductivity is design dependent but is generally several micro-mhos per centimeter.

The magnetic field is usually generated by the current alternating in the coils at line frequency. However, in some meters the line current is rectified and imposed on the coils as a "pulsed direct current" alternating between a positive value and zero at a frequency of (typically) several hertz. The claimed advantage of these meters is that each pulse of current lasts long enough for an induced voltage to be obtained free of transients and quadrature signals while the zero-current period is long enough for the noise signal to be obtained and subtracted from the measured signal, in effect providing an internal zero correction with concomitant reduction of drift and improved accuracy.

- 3.1.2 Probe-type meters. Although this report deals mainly with the tube-type flowmeters described above, the availability of other types of electromagnetic flowmeters is noted here. In these meters, an electromagnetic sensor measured a "local" velocity to which the average velocity in the conduit can be related, preferably by calibration. The following examples do not necessarily comprise an inclusive list. They include: cylindrical velocity probes inserted into the flow through the conduit wall or flow surface; "pitot" probes consisting of a short submersible flow tube intended for use in large open or closed conduits; stream-lined sensors mounted at the pipe invert near a manhole, for example. These kinds of meters are adaptable to conduits other than circular. In the case of free surface flows the depth must be monitored simultaneously. The types of fluids in which they can be used depends in part on the intrusiveness of the probe.

3.2 Advantages and Disadvantages of Electromagnetic Flowmeters

- 3.2.1 Flow-tube type meters are non-intrusive. This property makes them particularly attractive for use with sewage and sludge and also causes the head loss to be no greater than that for an equivalent length of plain pipe of the same diameter.

- 3.2.2 The output of tube-type meters can, under certain conditions, be made independent of pipe-roughness or Reynolds-number effects for axisymmetric flow; but the electromagnetic flowmeter does not necessarily measure a true average velocity for all velocity distributions. See sections 5.1 and 6.2. However, the output is independent of fluid density and is essentially linear.
- 3.2.3 In probe-type meters, the sensing element can be readily withdrawn for monitoring and cleaning. However, it may be sensitive to changes in velocity distribution.
- 3.2.4 Non-conductive liquids and most gases cannot be metered electromagnetically.
- 3.2.5 The instrument can be subject to extraneous electrical effects that are not always obvious.
- 3.2.6 Servicing and trouble-shooting may require substantial equipment and skilled technicians.

4. GUIDELINES FOR SPECIFICATIONS

4.1 Flow Tube

4.1.1 Geometry.

- 4.1.1.1 The flow tube generally should have the same nominal diameter as the adjoining pipe. An exception can be made when a smaller diameter is necessary to maintain a higher velocity through the meter (section 5.4.1). Specifications for this exception are given in section 5.1.2. There are no restrictions on the length of the flow tube provided that a proper magnetic field can be developed; generally the length is greater than the diameter.
- 4.1.1.2 The manufacturer's literature should provide, for design purposes, the actual internal diameter corresponding to each nominal meter size. If this actual diameter is smaller than the upstream pipe diameter, and if the flowing material is abrasive, a protective orifice with diameter slightly smaller than that of the liner can be installed at the upstream flange to protect the leading edge of the liner. To insure that performance is not affected, calibration should be done with the protective orifice in place.
- 4.1.1.3 Flow tubes are usually flanged at the ends. Because the inner lining is usually carried around to the flange face to provide insulation, gasketing and torquing of the flange bolts become critically important; the manufacturer should provide detailed instructions and all necessary parts to avoid liner damage on installation. For flow tubes that are not flanged, instructions should similarly be provided as necessary.
- 4.1.1.4 Direction of flow must be indicated on the outside of the flow tube, unless the meter is completely bi-directional without adjustment.

4.1.2 Materials.

- 4.1.2.1 The flow tube must be made of non-magnetic material and the inner liner in contact with the flow must be non-conductive as well. The materials must be unaffected by line pressure.

4.1.2.2 The liner material also must be suitable for the flowing liquid in terms of resistance to corrosion, abrasion, etc. In some cases, glass or Teflon lining may be advantageous for sludge flow. Liners used for digested sludge should be capable of handling temperatures to 70°C. All liners should be able to resist low temperatures typical of the location.

4.1.3 Electrodes.

4.1.3.1 Electrodes are located diametrically opposite each other, and are either flush with the inner tube surface or protrude slightly into the flow. See figure 2. They must be insulated from the remainder of the flow tube. The protruding configuration is used to hydrodynamically increase the velocity around the electrode and enhance its self-cleansing capability. A protruding electrode should be rounded at the edge so that a curvilinear protuberance is presented to the flow. Electrode surfaces should never be recessed, since the resulting cavity may collect debris.

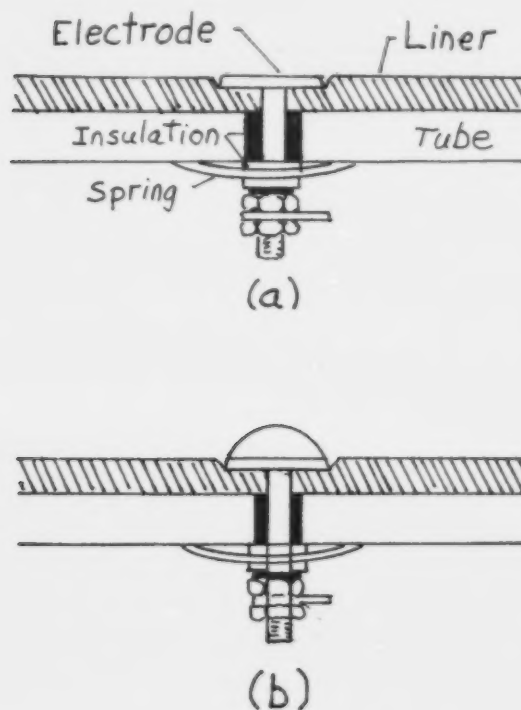


Figure 2. Electrodes

- 4.1.3.2 Electrodes must be made of corrosion-resistant material.
- 4.1.3.3 It is preferable but not mandatory that the electrodes be removable without taking the meter out of the line.
- 4.1.3.4 Small (in area) electrodes are recommended. In principle, the sensitivity of the flowmeter to velocity distribution can be eliminated by the use of large electrodes rather than the conventional or "point" electrodes. However, the problems introduced in keeping large electrodes clean are likely to outweigh the potential advantages and they are not recommended for wastewater treatment plants.
- 4.1.3.5 Internal electrode cleaning capability should be built in, particularly when frequent electrode inspection is not feasible. This internal cleaning can be accomplished by mechanical scrapers, ultrasonically induced vibrations, heating, or by other means. It can be either continuous, intermittent or manually actuated. Continuous operation is recommended for ultrasonic cleaners, since experience suggests that grease deposits, once formed, are difficult to remove by this method.
- 4.1.4 Grounding. All necessary grounding straps must be furnished with the meter. Complete instructions for earth grounding and methods for ascertaining the quality of the ground must be furnished. See also section 5.5.4.

4.2 The Secondary

- 4.2.1 The secondary system can be mounted integrally with the flow tube or separately from it. If it is mounted separately from the primary, the manufacturer must furnish specifications for all electrical connectors along with complete instructions, distance restrictions, etc.
- 4.2.2 The flow converter must include a display either in flowrate units or in units that can be readily converted to flowrate. It is preferable that the readout have switch-selectable flow ranges; however, the zero offset should be checked for each range. A flowrate display should be mounted near the flowmeter; this is in addition to any flowrate readout or flow totalizer in the central control room.
- 4.2.3 The secondary should be capable of being sealed against excessive humidity. In some instances, it will be necessary to specify that all meter elements be able to withstand temporary immersion for periods up to 48 hours at depths determined by the depth of pits or vaults that may be accidentally flooded.

- 4.2.4 Electrical connections and components must satisfy all code requirements for the particular area classification.
- 4.2.5 The secondary system should be able to operate within an ambient temperature range of -30°C to 60°C.

4.3 Calibration

- 4.3.1 The flowmeter should be hydraulically calibrated by the manufacturer prior to delivery to the customer.
 - 4.3.1.1 The conditions under which the factory calibration was performed, including upstream geometry, should be made known to the user.
 - 4.3.1.2 If a factory hydraulic calibration was not made, for whatever reason, the alternate means by which the meter rating was determined shall be fully explained to the user.
- 4.3.2 The manufacturer should furnish, or make available as an option, equipment for calibrating the flowmeter from the electrodes to the readout, or shall alternatively furnish instructions for performing such a calibration of the secondary system.
- 4.3.3 For probe-type flowmeters, the calibration data should include information on the effects, if any, of the radial probe location with regard to changes in pipe roughness or Reynolds number.

4.4 Accuracy

- 4.4.1 The accuracy of an electromagnetic flowmeter should be within one percent of full scale, but should not exceed three percent of flow. This means that if the flowmeter is to be used at flowrates lower than about one-third of full scale, a tighter accuracy specification will have to be put on the meter.
- 4.4.2 The repeatability shall be within one-half percent of full scale. For process control purposes, repeatability is often more important than accuracy. On the other hand, for measurements involving discharge-permit requirements or allocation of treatment costs or capacity among jurisdictions or industries, accuracy and repeatability are equally important.
- 4.4.3 The output should be independent of variations of up to 10 percent in line voltage and frequency, and of temperature variations within the ranges cited in sections 4.1.2.3 and 4.2.5.
- 4.4.4 If the manufacturer claims that electrodes and/or secondary elements are completely interchangeable, the accuracy limits for the system with interchanged parts should be furnished to the user.

5. INSTALLATION REQUIREMENTS

5.1 Approach Conditions

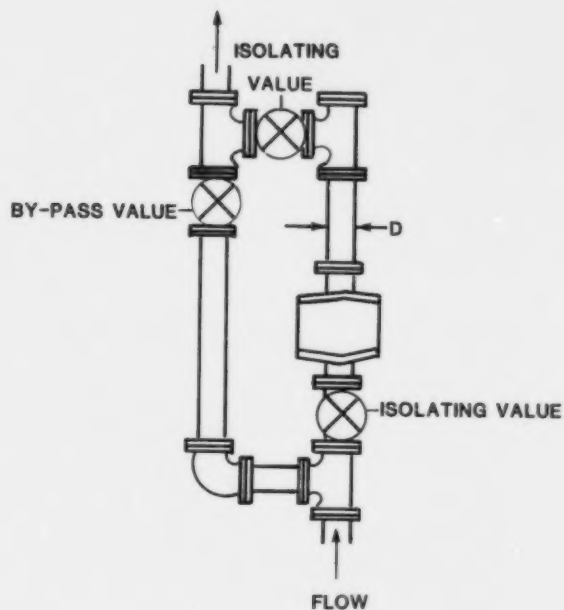
- 5.1.1 At least five diameters of straight pipe, measured from the plane of the electrodes, should precede and follow the tube. However, this approach length does not insure freedom from upstream effects, since errors described in section 6 can be introduced by severe upstream disturbances. If approach lengths shorter than 5 diameters are recommended for a specific commercial meter, data and/or a description of the experiments or analysis on which this recommendation is based should be furnished to the user.
- 5.1.2 An exception to the requirement of section 5.1.1 can be made in the case of a tapered axisymmetric reducer which is installed immediately upstream of a smaller flow tube in order to provide a self-cleansing velocity within the flow tube. The included angle of such a taper should not exceed 30 degrees, both upstream and downstream of the flowmeter.

5.2 Bypass

- 5.2.1 It is strongly recommended that piping and isolation valves be installed in such a way that flow can be bypassed around the meter. This arrangement not only permits removal of the meter when servicing is necessary, but also allows for convenient stopping of flow through the meter for zero checks. It is important that there be no leakage flow through the valves.
- 5.2.2 It is also recommended that a cleanout tee be installed near the flow tube. See figure 3 for one suggested layout. This accessibility is particularly important for meters that do not have electrode-cleaning capability or are subject to deposition or coating.

5.3 Orientation and Location

- 5.3.1 It is preferable that the flowmeter be installed in a vertical length of pipe. This orientation tends to equalize wear on the lining when an abrasive liquid is flowing and also prevents gases from collecting at the pipe crown.
- 5.3.2 If the flowmeter cannot be placed in a vertical pipe and must be inserted in a horizontal or inclined line, the following steps are recommended.



NOTE: RECOMMENDED 5 D UP AND DOWN STREAM

Figure 3. Typical installation.

- 5.3.2.1 Orient the meter so that the electrodes are on a horizontal line.
- 5.3.2.2 If the pipe is horizontal, install bleed valves at the crown near the flowmeter so that the line can be checked for accumulated gas.
- 5.3.2.3 In any event the flowmeter should always be located so that it will remain full, both during flow and when the flow is stopped. See also section 6.5.2.

5.4 Limiting Velocities

- 5.4.1 To assure scouring action, design for minimum velocities of at least 1.5 m/s (5 ft per second) for primary sludge and at least 0.9 m/s (3 ft per second) for other sludges and raw influent sewage.
- 5.4.2 To avoid excessive abrasion, velocities should never exceed 8 m/s (25 ft per second).

5.5 Other Considerations

- 5.5.1 Place the flowmeters on the high pressure side of pumps and control valves; this will minimize the effect of gas bubbles.

- 5.5.2 Avoid proximity to heavy induction machinery.
- 5.5.3 Refer to section 4.1.1.3 for mechanical installation procedures.
- 5.5.4 Proper grounding is essential (see section 4.1.4); improper grounding is one of the most frequent causes of failure of electromagnetic flowmeters in wastewater treatment plants. Grounding requirements may vary, depending for example on whether the pipe is metallic or nonmetallic, or on the meter material. An internal grounding ring (which also provides abrasion protection) may be required. In all cases the manufacturer's instructions must be followed closely.

6. ERROR SOURCES

6.1 General. The errors considered in this section are over and above the basic accuracy inherent in the instrument under optimum conditions of flow and use; this basic accuracy (as defined in 2.1) shall not exceed the limits given in section 4.4. It can be less than these limits if so indicated by in-place calibration or by complete data furnished by the manufacturer.

6.2 Velocity Profile

6.2.1 Background.

- 6.2.1.1 It has been shown theoretically that it is impossible to design an electromagnetic flowmeter with "point" electrodes that will be completely insensitive to all types of velocity profiles (1). Compromises can be attained as given in the following.
- 6.2.1.2 It has been shown theoretically that meters designed with a uniform magnetic flux are insensitive to the velocity profile provided it remains axisymmetric (2). This means that changes in viscosity or in (uniformly distributed) pipe roughness will not affect the flowmeter response. But in order to attain axisymmetry, long straight upstream approach piping is needed.
- 6.2.1.3 Commercial electromagnetic flowmeters are designed with non-uniform magnetic flux density in an attempt to even out the weight function and render the meters less sensitive to axisymmetric velocity distributions. This may result in losing the inherent insensitivity to axisymmetric changes described in section 6.2.1.2; however, this effect will generally be small -- well under 1 percent (1) of full scale.
- 6.2.1.4 Only limited data based on systematic experimental investigation of upstream effects are available in the literature, and even these show some disagreement. Sensitivity to upstream conditions depends in part upon meter design, and experimental results are not necessarily transferable to other types of meters. Nevertheless, the recommendations in section 6.2.2 are proposed as practical guidelines based on published information.

6.2.2 Effects of upstream pipe fittings.

- 6.2.2.1 For the purpose of this section, a straight approach length of 10 diameters will be considered to restrict errors due to velocity distribution to less than 1 percent and will be treated as an essentially error-free condition (3).
- 6.2.2.2 Axisymmetric fittings, e.g., expanders, reducers, etc., located at least 5 diameters upstream of the electrode plane probably will not measurably affect the performance, provided that any asymmetric fittings in the line are at least 5 diameters farther upstream. Fittings that introduce asymmetric disturbances, e.g., elbows, gate valves, etc., and are located 5 diameters (and up to 10 diameters) upstream can be estimated to add an additional 1 to 3 percent uncertainty to the flow (4). Fitting even closer to the electrode plane can cause substantial errors. For example, a half-closed gate valve located 1 diameter upstream can cause errors of 8 percent and higher (4). It is not possible to further quantify errors from these sources using published information. The size of the error may also depend upon the orientation of the eccentricity relative to the line connecting the electrodes.
- 6.2.2.3 The effect of swirl has not been established; an uncertainty of 1 percent should be allowed (5).
- 6.2.2.4 There is little information on effects of downstream fittings; a straight length of 3 diameters is suggested for asymmetric fittings.

6.3 Deposits

- 6.3.1 Deposits of non-conducting material on the electrodes will tend to insulate the electrodes and cause erroneous readings. Such deposits can be minimized by electrode shape (section 4.1.3.1), automatic cleaning capability (section 4.1.3.5), or maintenance of high flow velocities.
- 6.3.2 Deposits of non-conducting material on the tube liner (but not on the electrodes) will not affect the result unless the deposit becomes thick enough to measurably change the tube diameter and affect the output obtained from equation [2]. Such accumulations are discouraged by maintenance of high flow velocities.
- 6.3.3 Deposits of non-conducting material on the (originally conducting) pipe immediately upstream or downstream of the flowmeter will cause the liquid to lose its grounding. Where this problem is anticipated, the grounding should be done with grounding spikes or rings (or their equivalent) protruding into the flow.

6.3.4 The effect of conductive deposits within the flow tube depends in part on the ratio of the conductivity of the deposit to that of the liquid. Deposits of the same conductivity as the liquid may introduce no error except for that associated with change of diameter. However, conductive deposits can cause shorts to develop between the electrodes, or between the electrodes and ground, and they should be discouraged by the use of high velocities, elevated temperatures, or frequent cleaning.

6.4 Air or Other Gases

6.4.1 Air or gas bubbles diffused through the flow will not introduce an error in the volumetric flowrate measurement. However, mass flowrates deduced from these measurements will be in error. See section 5.5.1. If gas collects so that the pipe is not full (as distinguished from bubble dispersion), an error will be introduced even if the electrodes remain submerged. See section 5.3.

6.4.2 Small gas bubbles effervescing from the liquid and adhering to the electrodes will introduce errors by partially insulating the electrodes. Maintenance of recommended velocities (section 5.4.1) should preclude this occurrence.

6.5 Zero Drift

6.5.1 Zero drift is a commonly occurring error source in electromagnetic flowmeters, and it can be monitored only by frequent checking with the flow stopped. Flowmeters that have built-in zero correction as described in section 3.1.1 may require only infrequent monitoring. See section 7.1.2.7.

6.5.2 There is limited evidence that alternate immersion and drying of the electrodes encourages the formation of thin coatings that contribute to zero drift (5). However, keeping the flowmeter tube full at all times, even during extended periods of no flow, is suggested only for clean flows in non-corroding lines. In view of the proclivity of sewage and sludge to form grease deposits, these flows should be stopped under meter-full conditions only long enough for zero checks. A clean water flush is required following longer term shut down.

7. CALIBRATIONS AND PERFORMANCE CHECKS

7.1 Hydraulic Calibration of the Measuring System

7.1.1 General.

7.1.1.1 Even though a flowmeter is delivered pre-calibrated hydraulically by the manufacturer in accordance with section 4.3.1, an in-place hydraulic calibration provides the most assured method of evaluating its performance.

- Hydraulic in-place calibration is recommended when the system is first installed, at which time it provides not only an initial calibration but also an acceptance test.
- Hydraulic calibrations are recommended also at times subsequent to the initial calibration, if electrodes or secondary elements are changed, or if monitoring indicates an unexplained change in the measured flow-rate.
- General procedures for hydraulic calibration are described in section 7.1.2. Methods of obtaining reference flow measurements for hydraulic calibrations are given in section 7.3.
- Exceptions to the requirement for hydraulic in-place calibration are given in section 7.2.

7.1.1.2 It is emphasized that even an in-place hydraulic calibration reflects the performance of an electromagnetic flowmeter only so long as the electrodes and the tube interior are not adversely affected and remain effectively in the same condition as during calibration. Therefore, continued monitoring and follow-up calibrations are important, especially in sewage and sludge flows.

7.1.2 General procedure for hydraulic calibration.

7.1.2.1 Be sure that the electromagnetic flowmeter has been set up and that preliminary checks have been made completely in accordance with manufacturer's instructions.

7.1.2.2 With the line full but with the discharge valves closed (pump, if not positive displacement, should be running) check the zero-flow reading of the instrument. If there

is a zero offset, correct it according to manufacturer's instructions.

- 7.1.2.3 Set up a flowrate through the meter that is within the anticipated working range of flows. Allow enough time for it to become steady, and measure the reference or "true" flowrate, Q_R , by one of the methods in section 7.2.3.
- 7.1.2.4 During the time that the measurement of Q_R is being made, the flowrate as measured by the electromagnetic flowmeter, Q , should be recorded. If the measurement of Q_R is made by a method that requires a substantial length of time, e.g., the volumetric method, readings of Q should be made at intervals during the test period and an average value determined.
- 7.1.2.5 Compute the percentage difference in the two flowrates from $100 (Q - Q_R) / Q_R$ and enter this value on an error vs. flowrate curve as shown in figure 4.
- 7.1.2.6 The procedure of sections 7.1.2.2 through 7.1.2.5 should be done for a minimum of three flowrates (low, medium and high) within the anticipated working range. It is preferable that numerous runs be made (above the minimum three) to provide an indication of repeatability as shown in figure 4. (As a practical matter, however, it is recognized that some of the calibration flow measurements of section 7.2 are very time and resource consuming and that repeated runs may not be feasible.) Draw curve A averaged through the points.
- 7.1.2.7 A zero check (section 7.1.2.2) is recommended between each run in order to check the short-term zero drift.
 - If there is substantial zero drift, it should be ascertained whether it is due to local conditions, such as changes in nearby inductive machinery, which should not necessarily be charged against the flowmeter.
 - If the zero drift appears to be characteristic of the instrument itself, it should be monitored before each test point but no adjustment should be made.
 - Even if a flowmeter has automatic internal zero correction, a no-flow reading is desirable as an initial check on the correction.
- 7.1.2.8 Estimate the percentage error in measuring Q_R and enter it as curve B in figure 4.
 - This error estimate for Q_R is especially important in acceptance tests, since the flowmeter under test cannot be held to an accountability stricter than the user's ability to check it.
 - The estimated error will clearly depend upon which method of section 7.3 is used and the manner in which

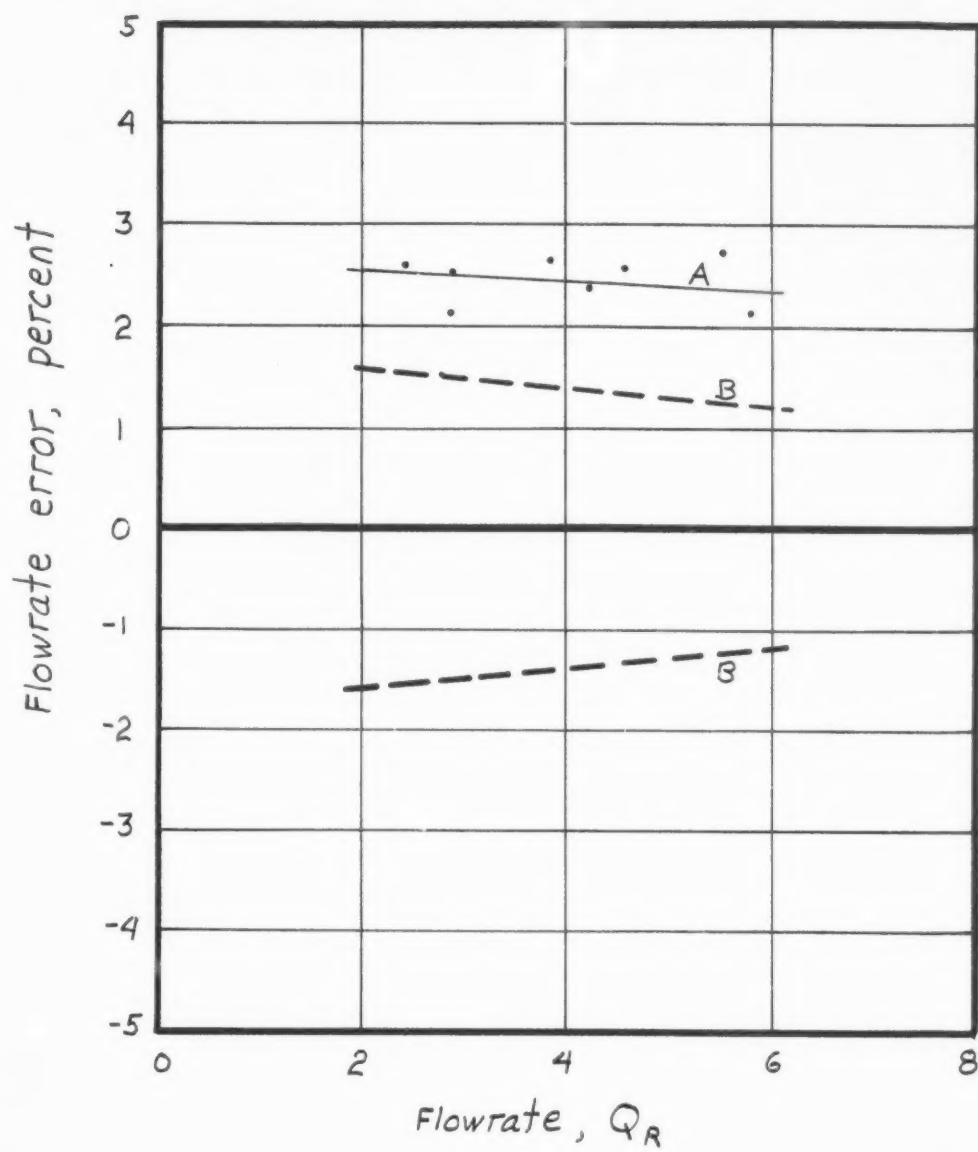


Figure 4. Flowmeter error determination.

it is executed. It may or may not vary with flowrate. Some of the methods, e.g., several of the transfer-standard devices, have documentation that provides guidelines for estimating errors (7,8). In any event, estimated errors that are agreeable to the involved parties must be assigned to Q_R .

7.1.2.9 If curve A is outside of curve B by more than the amounts allowed in section 4.4.1 (or alternate specifications), the performance may be unsatisfactory and these options should be considered.

- If the test results in figure 4 suggest a constant percentage error, it may be that a span adjustment of the secondary is required. The manufacturer's manual should provide instructions by which the user can make this adjustment. The calibration process of section 7.1.2 should be repeated after such an adjustment.
- If the flowmeter cannot be brought within specifications with adjustments made by the user, it must be repaired or rejected. However, if the data differences can be ascribed to faulty approach conditions and/or are otherwise consistent and repeatable, the calibration results can be used to develop a new, in-place rating for the flowmeter.

7.1.2.10 The error comparison described in sections 7.1.2.8 and 7.1.2.9 should be regarded as a suggested procedure only. Other comparison procedures that are agreeable to the involved parties are acceptable; the important point is that the reliability of the reference measurement must be taken into account in some way.

7.2. Calibration Other Than Hydraulic

7.2.1 It is recognized that there are situations where in-place hydraulic calibrations are not feasible and the user must resort to other methods.

7.2.1.1 One alternative is to calibrate the secondary only, using an electronic "flow simulator" offered as an option by the manufacturer or following instructions provided by the manufacturer to accomplish the same result. (See section 4.3.2). This alternative should be used in a place of a complete calibration only when there is reasonable certainty as to the condition and performance of the primary. This requires (assuming the flux strength can be verified) that the electrode and flow tube surfaces be closely monitored and that the adjacent piping is suitable.

7.2.1.2 If there are upstream pipe fittings, valves, etc., closer than 5 diameters to the electrodes, and particularly if these fittings produce asymmetric flows, the calibration should include the entire measuring system, i.e., primary as well as secondary.

7.2.2 Situations such as those described in section 7.2.1.2 can be approached also by "dry calibration" techniques, which involve direct measurement of the magnetic field strength in combination with weight functions and velocity distributions to arrive at a flowrate. Details of this method are beyond the scope of this report. See, e.g., (6). The velocity-distribution data needed for this method normally would be difficult to obtain, particularly in a sludge. However, it may be feasible to estimate a "worst case" velocity distribution based on published information so that error limits can be estimated.

7.3 Flow Measurement Methods for Hydraulic Calibrations

7.3.1 General.

7.3.1.1 The purpose of section 7.3 is to provide a general overview of methods available for obtaining the reference flowrate, Q_p , needed in section 7.1. The methods most likely to be applicable here are:

- Volumetric
- Comparison with a reference flowmeter
- Dilution
- Salt velocity
- Velocity traverse

7.3.1.2 The methods described vary considerably in accuracy and difficulty. Advantages, disadvantages, and areas of application of each method are cited. The method selected by the user will depend upon the purpose of the calibration, the type of liquid flowing, and the resources available to conduct the tests.

7.3.1.3 For highest accuracy, the in-place hydraulic calibration should be conducted with the actual process liquid.

7.3.1.4 If the calibration flowrate measurements are made at a location in the plant that is not directly in the line containing the electromagnetic flowmeter, equivalence of the flowrate at the measurement location to that through the flowmeter must be assured.

7.3.2 Volumetric calibration.

7.3.2.1 The feasibility of volumetric calibration of course depends upon the availability of suitable tank space and connecting conduits. Of the methods described here, it is probably

the one most suitable for difficult sludges. The potential accuracy is high, provided that:

- The tank is regular in configuration so that its lateral dimensions can be measured within acceptable limits of accuracy.
- The tank is large enough to permit a test run of sufficient length for the effect of timing errors at the start and finish to be kept within acceptable limits.
- The change in liquid level during the run is large enough so that the starting and finishing depths (probably obtained by the "on-the-run" method) can be measured within acceptable relative error limits.
- The flowrate remains relatively constant during the run. (See section 7.1.2.4.)
- It is noted that gravimetric tests can be substituted for volumetric where suitable tanks and scales are available.

7.3.2.2 Estimate the uncertainty of the resulting Q_p from a combination of the estimated errors of measurement of the lateral area, the depth change, the elapsed time. This uncertainty should be used in figure 4 as indicated in section 7.1.2.

7.3.3 Comparison with a reference meter (transfer standard).

7.3.3.1 In this context a reference meter is a flowrate measuring device whose performance can be referenced to published standards or to recommended practices that are acceptable to the involved parties. Examples include:

- Standard venturi tubes and venturi nozzles (7,8)
- Orifice plates (7,8)
- Parshall flumes (9)
- Thin plate weirs (10)

7.3.3.2 Flowmeters used as reference devices must meet all requirements of the accepted standard practices in fabrication, installation and use, so that their flow coefficients and uncertainties can be used for determining Q_p . In practical treatment-plant situations, it may be difficult to find or install a reference flowmeter meeting all of these requirements. For example, the stringent upstream approach conditions may not be met. In that case, the flowmeter cannot be used as a transfer standard unless rationally based and defensible modification to the flow coefficients and uncertainties can be agreed to by the involved parties.

7.3.3.3 When a differential-pressure type of flowmeter is used as the reference device, measure the pressure difference with a U-tube manometer. If a commercial secondary device is used in place of a manometer, it must have had

a recent calibration and complete information on its performance must be available; its error should be included in the Q_R uncertainty.

- 7.3.3.4 When a standard weir or Parshall flume is used as the transfer flowmeter, measure its head with a point gage (carefully zeroed to the crest) or equivalent device and determine Q_R from standard equations. If a commercial secondary device is used, see section 7.3.3.3.
- 7.3.3.5 It may be acceptable to use as a reference device a flowmeter for which there are no published standards, e.g., acoustic flowmeters, segmental orifices, provided: the device has been recently calibrated and its current accuracy and repeatability can be quantified to the satisfaction of involved parties; and the device is used under effectively the same conditions for which it was calibrated.

7.3.4 Dilution method.

- 7.3.4.1 In the dilution method the flowrate is deduced from the dilution of measurable properties (e.g., color, conductivity, or fluorescence) or tracer chemicals added to a turbulent flow in known amounts. The calibration can be done by either the constant-rate injection method, or the slug injection method. The constant-rate method is recommended here because it appears more practical for in-plant use. See reference (11) for details.
- 7.3.4.2 In the constant rate injection method, a tracer solution of accurately known concentration is injected upstream at a rate which is constant and accurately measurable. At a downstream distance long enough for complete mixing, the flow is sampled and the concentration "plateau" is attained. The flowrate, Q , is then determined from

$$Q = q(c_1 - c_2)/(c_2 - c_0) \quad [3]$$

where: q is the rate at which the sample of concentration c_1 is injected; c_2 is the measured "plateau" concentration downstream; and c_0 (which may be close to zero) is the background concentration of the tracer chemical existing in the flow.

- 7.3.4.3 This method requires accurate measurement of q and of all concentrations; skilled personnel and specialized equipment are needed. However, under optimum conditions the potential accuracy is high. See reference (11) for methods of estimating errors.

7.3.4.4 The tracer property must be conservative, since losses by absorption to solids in the flow will result in an apparent reduction in c_2 . The fluorescent dye Rhodamine WT has been used successfully in sewage without losses; its behavior in sludge is not known.

7.3.5 Salt-velocity method.

7.3.5.1 In the salt-velocity method, brine is injected suddenly at an upstream station in such a way that it becomes well-distributed across the section very rapidly. The time of passage of the salt pulse between two downstream stations is measured by means of electrodes which detect the increased conductivity associated with the passage of the brine. The flowrate then can be determined provided the volume of the conduit between the electrodes is accurately known. This method has a potential for 1 percent accuracy under optimum conditions. The accuracy actually obtained depends upon the transverse mixing and coherence of the injected brine slug, upon the accuracy of determination of the centers of gravity of the tracer conductivity and the time separating them, as well as upon the accuracy of the aforementioned volume determination.

7.3.5.2 Published standards for the salt-velocity method are written for circular pipes flowing full (8,12), and these or similar references must be consulted for details of the method. A sufficient length of (preferably straight) pipe upstream of the first electrode is necessary to insure complete lateral mixing of the salt slug when it reaches the electrode. This length can be short as four diameters when the injection is done internally in the standard manner (8,12). However, a substantially longer approach distance is needed if injections are made from the periphery of the pipe. The distance between the two sets of electrodes must be at least four diameters.

7.3.5.3 The liquid being measured must have a significantly smaller electrical conductivity than the brine.

7.3.5.4 The brine injection must be sudden, with an injection interval of the order of 1 second and no leakage thereafter.

7.3.5.5 The electrodes must provide equal increments of conductivity for equal segments of cross-sectional area. This requires the electrodes to be intrusive, so that the method cannot be used in raw sewage or sludge. However, it is suitable for treated effluent.

- 7.3.5.6 In principle, this method can be adapted to other shapes of conduits or channels provided that the approach length and the electrode spacing and configuration are modified to compensate for the shape change in a manner that is hydrodynamically sound and agreeable to the involved parties.

7.3.6 Velocity-area method.

- 7.3.6.1 The velocity-area method is applied to a flow cross section by measuring a number of velocities over the section, each representative of the average velocity within an incremental area, and summing the resulting velocity-area products. The method can be applied to both open and closed conduit flows, but it is much more convenient in accessible open channels.
- 7.3.6.2 This method is likely to be suitable mainly for electromagnetic flowmeters of relatively large capacity discharging a fairly clean liquid.
- 7.3.6.3 The velocity can be measured by point-velocity measuring instruments such as current meters (rotating or electromagnetic), pitot tubes, etc., or by acoustic velocity meters that measure an average velocity component along a line path.
- The point velocity instruments are intrusive and generally could not be used effectively in raw sewage or sludges. However, there may be an opportunity to use a rotating-element or electromagnetic current meter in an open channel discharging treated effluent. In that event, see section 7.3.6.5.
 - Pitot tubes are usually restricted to full conduit flows, where velocities are more likely to be high enough to generate a readily measurable dynamic pressure.
- 7.3.6.4 The accuracy of this method depends upon whether the sampling points are distributed so as to yield an average velocity and whether each velocity is accurately measured. The latter depends in part on the accuracy of the velocity-measuring instrument itself and upon the duration of the sampling time at each point. The sampling requirements tend to make it a lengthy measurement, so it can be used only where sufficiently long periods of essentially steady flow are available.
- 7.3.6.5 In cases where a point-velocity instrument is used in an open channel, the following conditions must be observed.
- The average velocity in the section preferably should exceed 0.30 m/s (1 ft per second).

- Only velocity-measuring instruments that have been recently calibrated and whose present accuracy and uncertainty can be estimated to the satisfaction of involved parties should be used.
- Consult reference (12) for distribution of velocity sampling points in the cross section, and reference (13) for error estimates.

7.4 Flow Measurements for Monitoring

7.4.1 General.

- 7.4.1.1 Measurements for monitoring are defined in this context as those that are made subsequent to an initial calibration for the purpose of detecting anomolous behavior of the electromagnetic flowmeter. These measurements in themselves cannot furnish a calibration coefficient as can those listed in section 7.3. Nevertheless, the measurements must be carefully made so that their precision can be depended upon.
- 7.4.1.2 Frequent monitoring is especially important for users of electromagnetic flowmeters, since the system is electrical as well as generally obscured from view and consequently the quality of its performance is not as visible and readily checked as, say, an open channel flume with a float gage.
- 7.4.1.3 Measurements for monitoring frequently involve measuring a pressure difference at a location where the flowrate has a unique and repeatable relationship to that difference so long as the geometry remains unchanged. This requirement for constant geometry means that, in the case of valves, the settings for disc or gate position must be reproducible. It also means that there cannot be internal deposits or coatings that significantly affect the measured pipe diameter. Locations for monitoring can include, among others:
- Pipe elbows, usually 90 degrees (see also section 7.5.2)
 - Butterfly or gate valves (when partly closed)
 - Pumps
 - Pipe reducers
- 7.4.1.4 The capability for monitoring should be set up prior to calibration, so that a relation between the pressure difference at the monitor and the reading of the newly installed electromagnetic flowmeter can be established from the results of the hydraulic calibration (section 7.1.2) or by other means (section 7.2).
- 7.4.1.5 It should be noted that this type of monitoring procedure is valid only so long as the viscosity of the

liquid does not change radically; caution should be exercised with sludges.

7.4.2 Measuring the pressure difference.

7.4.2.1 Pressure taps.

- Pressure taps should be flush with the inner surface of the pipe and free of burrs. Hole diameter is not critical because we are looking for repeatability rather than accuracy; diameters of from 0.5 cm to 1.0 cm for small to large pipes are usually adequate. The condition of the inner surface at the tap must remain essentially the same and should be monitored to that end. For example, rust or grease ridges or tubercles at or near the hole will affect the reading.
- Pressure taps for elbows are installed as shown in figure 5. For the other locations cited in section 7.4.1.3, the taps are placed upstream and downstream of the device producing the pressure difference.
- For sewage and sludges it is recommended that only one pressure tap be used at each upstream and downstream point. (Elbows use only one tap at each position in any event.) The use of several taps evenly spaced around the circumference and connected by a piezometer ring is preferably restricted to relatively clean liquids.
- Single pressure taps in horizontal or near-horizontal lines should be located in a horizontal diametric plane, or slightly above that position, in order to minimize entry of gases and solids into the manometer lines.

7.4.2.2 Differential-pressure sensor.

- The pressure difference can be measured using conventional U-tube manometry, for example, a water-air manometer or, for large differences, a water-mercury manometer. Manometer fluids should be selected so that the manometer deflection is never less than approximately 3 inches (7.6 cms). The glass tubes should be large enough to avoid meniscus shape errors.
- The pressure difference can be measured also with one of various types of commercial differential pressure cells. Such sensors should be calibrated frequently against a liquid-column manometer. This is best accomplished by providing fittings in the connecting tubing so that a manometer can be placed conveniently in parallel with the sensor.
- Always bleed manometer lines of gas before each use, and check for zero deflection before and after each use.

- Make several manometer readings (more, if the columns are oscillating) for each measurement and use the average.

7.4.2.3 Connecting tubing.

- The recommendations for the connecting tubing between the pressure taps and the manometer or sensor are intended to discourage accumulations of gas or sediment in the lines.
- To that end, lengths of horizontal tubing should be avoided in favor of moderate slopes. Further, elevation peaks (inverted U's) in liquid lines should have gas bleed valves, and troughs should have sediment drains or traps.
- The connecting tubing should be corrosion resistant and its bore should be at least 3/8 inch (1 cm). It should be valved in a way that permits all portions of the lines to be flushed when necessary.
- Valves and by-pass tubing should be provided so that the manometer or sensor can be isolated from the pipe flow for zero checks.
- Clean water should be kept in the lines by the purge flow (see section 7.4.2.4).

7.4.2.4 Purge flows.

- Continuous purging of pressure taps is required in sewage and sludge flows. This purging should be done with tap water or clean non-potable water.
- The pressure loss in the tubing between the purge-water connection and the tap should be the same in both of the lines so that the pressure differential is essentially unaffected by the purge flow. This can be accomplished by making the two paths geometrically similar and by keeping the purge flowrate the same in both legs. Install a variable area flowmeter (or equivalent) and a control valve in each of the purge water lines for flow adjustment.
- Purge flows should be high enough to keep dirty liquid out of the connecting lines under all conditions; however they should remain negligible relative to the primary flow.

7.5 Approximate Flow Measurements

- 7.5.1 It is useful on occasion to have a relatively quick and inexpensive way of knowing whether a flowmeter is even approximately correct, particularly when an in-place calibration cannot be made. Measurements in the range of ± 10 percent uncertainty may be adequate for this purpose. Some of the monitoring locations listed in section 7.4 are adequate for this purpose, as shown in the following examples.

7.5.2 Elbow meters.

7.5.2.1 The accelerations associated with flow around a curve of radius r cause a pressure difference in the radial direction which can be used to deduce a flowrate (as well as monitor) in a full pipe. This method, which has been investigated mainly for 90-degree elbows, requires an arrangement as shown in figure 5.

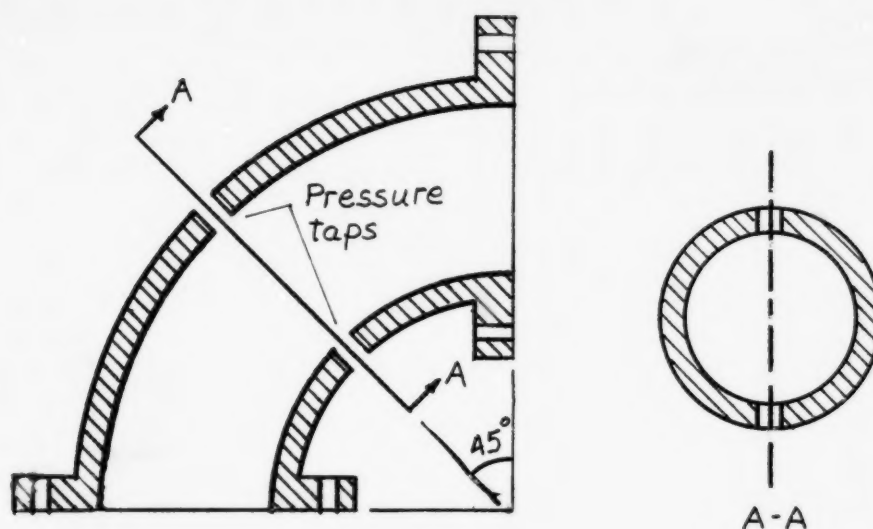


Figure 5. Elbow meter.

7.5.2.2 The flowrate can be estimated from the following analytically determined expression (14).

$$Q = (r/2D)^{1/2} (\pi D^2/4) (2g\Delta h)^{1/2} \quad [4]$$

Here, r is the radius of curvature of the elbow centerline, D is the elbow (and pipe) diameter and Δh is the measured head difference in terms of height of flowing liquid.

7.5.2.3 The elbow performance is more sensitive to the radius of curvature of the inside bend than to that of the outside bend. Therefore it is desirable, when practicable, to determine r by measuring the inner bend curvature and adding half the diameter rather than to use a nominal value of r .

7.5.2.4 The elbow should be preceded by about 10 diameters of straight upstream pipe. There is insufficient information with which to evaluate such effects as pipe roughness and Reynolds number, except to note that with decreasing Reynolds number the flow is less than that predicted by equation [4]. Therefore added caution must be exercised in its application to sludge flows.

7.5.2.5 Examination of published experimental results suggests that equation [4] cannot be depended upon for accuracies better than roughly ± 10 percent. However, it should be noted that an elbow meter that is carefully fabricated and installed and properly calibrated can be as effective a flowmeter as other types of pressure-differential devices. The foregoing paragraphs of section 7.5.2 pertain to uncalibrated elbows only.

7.5.3 Valves. Butterfly valves are sometimes furnished with flowrate vs. angle-of-opening data which can be used for approximate checks on flowmeters. Such measurements would of course be affected to an unknown extent by upstream pipe conditions and viscosity.

8. OPERATION AND MAINTENANCE

8.1 Operation/Maintenance Frequencies

8.1.1 Flowmeters without monitoring stations (section 7.4).

8.1.1.1 The frequency of required routine operation checks and maintenance can best be determined from experience. However, until experience provides guidelines, relatively frequent checks must be made, particularly where there is no monitoring station.

- Stop flow through the meter briefly at least once a day to check for zero drift. This should be done initially even for meters that have internal zero correction in order to check for possible offsets; the frequency of subsequent checks can be reduced as appropriate.
- Check the secondary span weekly. See section 4.3.2.
- Visually inspect the liner and electrodes monthly and clean as necessary.

8.1.1.2 The frequency of the above checks can be adjusted as a data base is developed.

8.1.2 Flowmeters with monitoring stations.

8.1.2.1 If there is a monitoring station as described in section 7.4, the initial operation checks can consist of a daily comparison of the electromagnetic flowmeter reading with the monitor, provided that the satisfactory condition of the internal surfaces and the pressure taps of the monitor can be assured. If this condition is satisfied, the operations in section 8.1.1.1 need not be done at specified intervals until the previously determined relation (section 7.4.1.4) between the flowmeter and monitor readings changes, at which time zero and secondary span checks should be made, followed by inspection and cleaning if necessary.

8.1.2.2 If the internal condition of the monitoring station cannot be verified satisfactorily, treat the flowmeter according to section 8.1.1 and use the monitor only to detect gross malfunctions.

8.2 Miscellaneous Operation/Maintenance Recommendations

- 8.2.1 Follow all maintenance procedures recommended by the manufacturer in the user manual, in addition to those in section 8.1.
- 8.2.2 If the flowmeter has been off line, always turn on the electrical supply several hours before the readings are started.
- 8.2.3 Measure the actual internal diameter of the flow tube before it is installed.
- 8.2.4 If the flowmeter is in a horizontal line (not recommended) vent the gas bleeds (section 5.3.2.2) at least once per shift until a more realistic frequency is learned from experience.

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